

DISPERSE, AGGREGATE AND DISPERSE (DAD) CONTROL STRATEGY FOR
MULTIPLE AUTONOMOUS SYSTEMS TO OPTIMIZE RANDOM SEARCH

TO WHOM IT MAY CONCERN:

BE IT KNOWN THAT CHRISTIANE N. DUARTE citizen of the United States of America, employee of the United States Government, resident of Fall River, county of Bristol, Commonwealth of Massachusetts has invented certain new and useful improvements entitled as set forth above of which the following is a specification:

JAMES M. KASISCHKE, ESQ.
Reg. No. 36562
Naval Undersea Warfare Center
Division, Newport
Newport, RI 02841-1708
TEL: 401-832-4736
FAX: 401-832-1231

09/226,623

1 Attorney Docket No. 78693

2

3 DISPERSE, AGGREGATE AND DISPERSE (DAD) CONTROL STRATEGY FOR
4 MULTIPLE AUTONOMOUS SYSTEMS TO OPTIMIZE RANDOM SEARCH

5

6 ABSTRACT OF THE DISCLOSURE

7 A method for conducting a search of an area for targets by
8 a number of vehicles. First each of the vehicles randomly
9 disperses from the other vehicles. Then during an aggregate
10 phase, each vehicle responds in a predesignated way to an
11 encounter with one of the other vehicles. A number of specific
12 search strategies may be followed which tend to direct the
13 search in a particular designated direction or allow a
14 successful searching vehicle to set the direction of the search.
15 This method results in improved performance in conducting
16 searches by robots or other vehicles.

1 Attorney Docket No. 78693

2

3 DISPERSE, AGGREGATE AND DISPERSE (DAD) CONTROL STRATEGY FOR

4 MULTIPLE AUTONOMOUS SYSTEMS TO OPTIMIZE RANDOM SEARCH

5

6 STATEMENT OF GOVERNMENT INTEREST

7 The invention described herein may be manufactured and used
8 by or for the Government of the United States of America for
9 governmental purposes without the payment of any royalties
10 thereon or therefor.

11

12 BACKGROUND OF THE INVENTION

13 (1) Field of the Invention

14 The present invention relates to travel control methods and
15 in particular to such methods which are used to control search
16 vehicles.

17 (2) Brief Description of the Prior Art

18 When searching an area for an object such as a mine, it is
19 often desirable to search an area using expendable units. These
20 units should have a relatively low cost, but they should also be
21 capable of searching an area in an efficient fashion.

22 One way of searching an area is by an ordered search
23 algorithm such as a grid. Grids are not readily adaptable to

1 rough terrain, and the party positioning the search object can
2 optimize placement of search objects to reduce grid efficiency.

3 Another method of searching an area is by random dispersal.
4 Random dispersal requires little control and accommodates any
5 terrain type. The problem with random dispersal is that it is
6 inefficient. Some areas go unsearched while other areas are
7 subjected to multiple searches.

8 Various methods and apparatus are disclosed in the prior
9 art for controlling robotic vehicles.

10 U.S. Patent No. 5,321,614 to Ashworth, for example,
11 discloses a control apparatus and method for autonomous
12 vehicles. Obstacle sensors onboard each vehicle produce signals
13 associated with obstacles used for navigation.

14 U.S. Patent No. 5,329,450 to Onishi discloses a control
15 method for multiple robots in which a central control station
16 distributes remaining tasks to robots having no task.

17 U.S. Patent No. 5,367,456 to Summerville et al. discloses a
18 control system for automatically guided vehicles. A stationary
19 control computer schedules the activities of individual robots.

20 U.S. Patent No. 5,568,030 to Nishikawa et al. discloses a
21 travel control method for a plurality of robots. Each
22 destination route is searched for availability prior to being
23 used to control a robot's travel path.

1 U.S. Patent No. 5,652,489 to Kawakami discloses a mobile
2 robot control system in which each robot emits a signal. The
3 signal is used to stop movement of other robots about to
4 traverse the same route.

5 None of these methods provides a control method using a
6 decentralized method of controlling low cost robots.

7

8 SUMMARY OF THE INVENTION

9 The object of this invention is to define a control
10 strategy framework that will improve the performance of multiple
11 robots when searching an area. This framework builds on a
12 random search strategy by introducing two kinds of phases: a
13 disperse phase and an aggregate phase. During the disperse
14 phase, the vehicles perform a random search, which will result
15 in the group dispersing over the search area. During the
16 aggregate phase, the vehicles will continue to search, but will
17 also communicate with neighbors when they come into
18 communication range of each other. This is referred to as an
19 "encounter". During an encounter, two vehicles exchange
20 information and adjust their headings based on the current
21 encounter strategy. The combination of these phases results in
22 a group of robots performing a random search enhanced by intra-
23 group communication that will provide better group cohesion and

1 a more efficient search. The disperse, aggregate, and disperse
2 combination is referred to as the DAD-Control Strategy. The
3 DAD-Control Strategy framework allows variations in several
4 fundamental ways: the duration of each phase, combination of the
5 phases, (e.g., DADAD), and the selection of encounter strategies
6 during the aggregate phases.

7 The present invention comprises a method for conducting a
8 search of an area for targets by a plurality of vehicles. First
9 each vehicle disperses from the other vehicles. Then during the
10 aggregate phase each of the vehicles responds in a predesignated
11 way to an encounter with one of the other vehicles.

12

13 BRIEF DESCRIPTION OF THE DRAWINGS

14 Other objects, features and advantages of the present
15 invention will become apparent upon reference to the following
16 description of the preferred embodiments and to the drawing,
17 wherein corresponding reference characters indicate
18 corresponding parts in the drawing and wherein:

19 FIG. 1 is a schematic drawing illustrating an encounter
20 between two vehicles and a detection of a target in a preferred
21 embodiment of the method of the present invention;

1 FIG. 2 is a schematic drawing illustrating a preferred
2 embodiment of the method of the present invention, referred to
3 hereafter as the north strategy;

4 FIG. 3 is a schematic drawing illustrating another
5 preferred embodiment of the present invention referred to
6 hereafter as the best finder strategy;

7 FIGS. 4a and 4b are schematic drawings illustrating another
8 preferred embodiment of the present invention referred to
9 hereafter as the best finder or north strategy; and

10 FIG. 5 is a schematic drawing illustrating still another
11 preferred embodiment of the present invention referred to
12 hereafter as the best finder and north strategy.

13

14 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

15 The underlying philosophy in robot maneuvering logic is to
16 keep the logic simple. A powerful and yet simple to implement
17 control strategy for multiple vehicles searching as a group is a
18 random search strategy. There is little to no dependency on
19 neighbors in determining next position. Given enough time an
20 area can be completely covered much in the way a gas will fill a
21 volume. The robots in this simulation use random changes in
22 heading and random number of steps forward. This allows the
23 robot to wander in and out of an area. The goal is to improve

1 the efficiency of this simple search scheme by allowing
2 exchanges of information that will improve the efficiency of the
3 next move decision logic of the robot. This establishes a
4 minimal level of connectivity between group members. The
5 connectivity is established when two members come into range,
6 recognize each other and establish a communication link long
7 enough to exchange a pre-determined packet of information. Once
8 the information is transmitted, the connectivity is terminated.

9 The proposed control strategy is a combination of two types
10 of maneuvering phases: a disperse phase and an aggregate phase.
11 The natural side effect of a group of vehicles performing a
12 random search is that the vehicles spread out or disperse over
13 time. The disperse phase produces such an emergent behavior as
14 each vehicle follows a random search with communication only
15 present to avoid the other vehicles, and the group disperses
16 over the search area. The aggregate phase maintains the random
17 search maneuvering, but then introduces opportunities for two
18 vehicles to exchange information through encounters.
19 Information exchange is primarily focused on adjusting the
20 heading of one or both vehicles based on the encounter strategy.
21 Other information categories can be investigated along with new
22 encounter strategies. By running a sequence of disperse,
23 aggregate and disperse (DAD) phases, the overall performance

1 should improve because the vehicles remain more concentrated or
2 guided during the random search phases.

3 During the disperse phase, a random walk scheme is used.
4 In this scheme, vehicles can randomly turn from -45 degrees to
5 45 degrees. Vehicles can also advance from 1 to 10 steps
6 forward. The upper limit of the turn has been tested at ranges
7 of ± 45 degrees, ± 90 degrees ± 180 degrees. The value can be set
8 according to the amount of dispersal and overlap for the
9 particular application.

10 During the aggregate phase, vehicles also use the random
11 walk scheme, but also communicate during encounters. An
12 encounter occurs when vehicles are within a predetermined
13 encounter distance to each other. This is defined as the
14 variable encounter zone, which has a constant value of 70 (units
15 of distance). The exchange of information is based on the
16 current encounter strategy.

17 When two vehicles are within the encounter zone distance
18 apart, the vehicles exchange information that impacts the
19 heading of one or both vehicles. An encounter threshold
20 variable is set that establishes to some degree the frequency
21 with which vehicles change heading based on an encounter with
22 the same vehicle. Sensitivity tests were made varying the
23 encounter threshold variable by values of 0, 5 and 10. This

1 signifies that two vehicles will not re-encounter for the number
2 of simulation cycles specified by the encounter threshold after
3 the initial encounter even if they remain in the encounter zone.

4 There are different strategies that were tested when two
5 vehicles encounter one another. These strategies were motivated
6 by operational requirements in littoral waters and studies of
7 animal behavior in a foraging scenario.

8 Referring to FIG. 1, a first vehicle 10 and a second
9 vehicle 12 are illustrated. Also illustrated are three targets
10 14, 16 and 18. The first vehicle 10 has a detection range 20
11 and an encounter zone 22. The second vehicle 12 has a detection
12 range 24 and an encounter zone 26. A detection occurs when one
13 of the vehicles, such as vehicle 10 approaches one of the
14 targets such as target 14 within the vehicle's detection range
15 such as detection range 20. An encounter occurs when two
16 vehicles such as first vehicle 10 and second vehicle 12 approach
17 within their respective encounter zones 22 and 26. An encounter
18 consists of a communication between vehicles 10 and 12, which
19 may result in adjusting the heading of one or more of the
20 vehicles, based on one of the strategies described herein. The
21 encounter threshold will also provide a delay (in simulation
22 cycles) to avoid re-encountering the same vehicles.

1 A first strategy, the north strategy, uses a preferred
2 direction to establish a new heading. In this strategy, upon
3 encounter each vehicle's heading is compared to a preferred
4 direction heading (i.e., north or 90 degrees) which specifies
5 the overall group's heading. The vehicle with the heading
6 closest to the preferred direction is used as the new heading
7 for the other vehicle.

8 By setting the overall group's heading to impact the
9 individual's heading adjustment, the group should eventually
10 advance in a sweeping motion in the direction of the overall
11 group's heading. In addition, following is introduced at a
12 small scale when two vehicles encounter and one adapts the
13 heading of the other. This creates a short instance of
14 following until the follower vehicle again adopts the random
15 search scheme. Another net affect should be the consolidating
16 of group members in the operational space or at least in
17 clusters.

18 Referring to FIG. 2, the north strategy is further
19 illustrated. In this strategy, the first vehicle 10 has an
20 initial heading 28, and the second vehicle 12 has an initial
21 heading 30. A comparison of these initial headings 28 and 30 is
22 made with the north or preferred direction 32. Since the second
23 vehicle 12 has an initial heading 30 which is closer to the

1 preferred direction 32 than the initial heading 28 of the first
2 vehicle 10, the first vehicle 10 changes direction to new
3 heading 34. The second vehicle 12 remains at its initial
4 heading 30.

5 A variation on the north strategy involves switching the
6 preferred direction when a preselected condition occurs. This
7 preselected condition can be the elapse of a period of time, the
8 finding of a predefined number of targets, or the occurrence of
9 a set number of encounters with other vehicles. This will
10 result in the overall group moving back to its point of origin.
11 This strategy is a slight variation on the north strategy, which
12 would allow a second pass over already explored area. This
13 variation may compensate for targets that are missed and
14 supports running multiple passes over the same area.

15 Another strategy, the best finder strategy, compares the
16 number of targets found by each vehicle and uses the direction
17 of the vehicle finding more targets. The heading of the vehicle
18 with the most targets found is used as the heading for the other
19 vehicles in the encounter. Based on observations from social
20 animals, there are members in a group that show higher success
21 at discovering food, and other members can be seen to mimic the
22 actions of this best finder. This strategy allows the vehicle
23 that has found the most targets to influence the heading of the

1 second vehicle during an encounter. This could be interpreted
2 as the best finder leading the second vehicle to a concentration
3 of targets. This strategy should improve target finding when
4 the targets have a clustered or patch distribution given
5 successful exchange between the best finder and second vehicle.

6 Referring to FIG. 3, the best finder strategy is
7 illustrated in which the vehicle with the most targets T found
8 sets the heading for the second vehicle. For purposes of
9 illustration, the first vehicle 10 has located four targets and
10 the second vehicle 12 has located six targets. The first
11 vehicle 10 has an initial heading 36 and the second vehicle 12
12 has an initial heading 38. The first vehicle 10 has a new
13 heading 40 which conforms to the initial heading 38 of the
14 second vehicle 12 since the second vehicle 12 has located more
15 targets.

16 Yet another strategy is the best finder or north strategy.
17 This strategy is a combination the north strategy and the best
18 finder strategy such that if both vehicles have found no targets
19 or have the same number of targets, the vehicles use the north
20 strategy since no one vehicle has out performed the other. If
21 there is a discrepancy in number of targets between the two
22 vehicles, the vehicles use the best finder strategy.

1 Referring to FIGS. 4a and 4b, the best finder or north
2 strategy is illustrated. In FIG. 4a the first vehicle 10 has an
3 initial heading 42 and the second vehicle 12 has an initial
4 heading 44 under conditions where the first vehicle 10 has
5 located four targets, $T=4$, and the second vehicle 12 has located
6 six targets, $T=6$. Because the second vehicle 12 has located
7 more targets, the first vehicle 10 assumes a new heading 46 that
8 conforms to the initial heading 44 of the second vehicle 12. If
9 both vehicles have located the same number of targets T , or if
10 no targets have been located, FIG. 4b is applicable. In FIG.
11 4b, the first vehicle 10 has an initial heading 48 and the
12 second vehicle 12 has an initial heading 50. Since the initial
13 heading 50 of the second vehicle 12 is closer to the preferred
14 direction or north 52, the first vehicle 10 will assume a new
15 heading 54 which conforms to the initial heading of the second
16 vehicle 12.

17 The best finder and north strategy is a variation of the
18 best finder strategy. The variation consists of setting the
19 best finder vehicle's heading to the preferred direction that in
20 this case is north 60. The other vehicle receives the best
21 finder's heading as its new heading. The motivation for this
22 strategy is to introduce some degree of delegating one vehicle's
23 actions to another. The vehicle with the most targets found

1 will send the second vehicle in the same direction since targets
2 have been found there to continue the local search. The vehicle
3 with the most targets will continue the global search by heading
4 in the preferred direction to locate other concentrations of
5 targets.

6 Referring to FIG. 5, the best finder and north strategy is
7 illustrated in which the best finder strategy applies except as
8 the best finder adjusts its heading to the overall group heading
9 of north or the preferred direction. In this example, the first
10 vehicle 10 has located four targets and the second vehicle 12
11 has located six targets. The first vehicle 10 has an initial
12 heading 56 and the second vehicle 12 has an initial heading 58.
13 Since the second vehicle 12 has located more targets T , it
14 assumes a new heading 60 that is in a preferred direction or
15 north 62. The first vehicle 10, which has located fewer targets
16 T , assumes a new heading 64 in the same direction as the initial
17 heading 58 of the second vehicle 12.

18 Another strategy concerns varying the vehicle's velocity
19 based on the search outcome. The logic behind this strategy is
20 that a vehicle should slow down and make a slow search if it
21 finds a high ratio of targets to time searched. Otherwise, the
22 vehicle should increase its velocity to advance to other areas
23 more rapidly.

1 In order to perform this strategy, each vehicle is
2 preprogrammed with an estimate, E , for the target density in the
3 search area. This is weighted by a selected estimate weight,
4 E_{wt} . Each vehicle has a value for experience, Exp , related to
5 The number of targets found T , for an elapsed time, t , and
6 weighted by E_{wt} , a weighting factor. Velocity, V , can then be
7 changed in accordance with the following equations, where ΔV is
8 the change in velocity:

TMW

$$Exp = \frac{T * Exp_{wt}}{t} \quad (1)$$

$$\Delta V = (E - Exp) * E_{wt} \quad (2)$$

11 Using these equations, it was observed that often the velocity,
12 V , increases rapidly, and the vehicle exits the search area.
13 Therefore, a maximum velocity can be set in the vehicle so that
14 the velocity of the vehicle plus the change in velocity is set
15 to the maximum if the maximum velocity would be exceeded.
16 Likewise, a minimum velocity can be set if the change in
17 velocity would bring the velocity below the minimum.

18 It will be appreciated by those skilled in the art that
19 this velocity adjusting algorithm can be applied to any of the
20 previous search strategies.

1 While the present invention has been described in
2 connection with the preferred embodiments of the various
3 figures, it is to be understood that other similar embodiments
4 may be used or modifications and additions may be made to the
5 described embodiment for performing the same function of the
6 present invention without deviating therefrom. Therefore, the
7 present invention should not be limited to any single
8 embodiment, but rather construed in breadth and scope in
9 accordance with the recitation of the appended claims.

SEARCHED INDEXED
SERIALIZED FILED